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RESEARCH ON THE PSYCHOPHYSIOLOGICAL BASIS OF HUMAN VIGILANCE

FINAL REPORT

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The research products of a program of studies directed at identifying the psychophysiological basis of human vigilance are briefly summarized. Much of the work focused on identifying the relationship between the biogenic catecholamines, adrenaline (A) and noradrenaline (NA), and human vigilance. A new fluorometric assay for subnanogram concentrations of (A) and (NA) was developed. Several studies were performed showing

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20. ABSTRACT (Continued)

Substantial correlations between vigilance performance and circulating concentrations of (A). It was shown that vigilance could be increased through pulsatile infusions of (A). Vigilance was shown to be adversely affected by typical urban concentrations of carbon monoxide (CO) and by hypoxia experienced at high altitudes. It was also shown that vigilance decrements occur not only with typical laboratory tasks (used early in the program) but also with realistic radar monitoring tasks. Target detection performance, using a typical radar PPI, was shown to deteriorate over time as excretion rates of (A) decreased. Concurrent monitoring of the EEG showed that the performance decrement was also accompanied by a decreased percentage of Beta and increased percentage of Alpha and Theta.

RESEARCH ON THE PSYCHOPHYSIOLOGICAL BASIS OF HUMAN VIGILANCE

(Final Technical Report)

This was an investigation into how psychophysiological mechanisms of vigilance enable man to remain alert in a monotonous work environment. It has been repeatedly demonstrated that these mechanisms fail to function efficiently in most men who are required to perform long watches under tedious conditions. Their detection performance, high at the outset of the watch, typically declines in an exponential manner to a level noticeably below the "alerted" level. From this it has been concluded that monotony impairs the function of the vigilance mechanisms, resulting in a performance decrement. A challenge for research, therefore, is to identify means for maintaining the function of these mechanisms in the face of prolonged monotony.

The objective of the research summarized here was to study the relationship between the biogenic catecholamines, adrenaline (A) and noradrenaline (NA), and human vigilance. It was believed that the catecholamines, directly or indirectly, act upon man's central nervous system to affect his state of vigilance and his detection performance. The objective was to demonstrate how the catecholamines affect vigilance, and how blood catecholamine concentration might be controlled to maintain vigilance at an optimum level.

It was hypothesized that vigilance is partially maintained by a positive feedback system involving the mesencephalic reticular formation, the hypothalmus, and the adrenal medulla. One of the implications of this hypothesis is that vigilance can be maintained by keeping the circulating concentration of adrenaline at a high level.

Several investigations of the correlation between catecholamine level and performance in watchstanding tasks were conducted. In the later phase of the research, the psychophysiological mechanisms underlying vigilance performance were extended to include study of the concurrent electroencephalogram (EEG). The early studies involved rather typical laboratory vigilance tasks; the latter work involved an operationally realistic radar monitoring task.

The technical papers and reports issued under this contract are summarized briefly below.

1. O'Hanlon, James F., Jr., Campuzano, Helen C., & Horvath, Steven M.* A fluorometric assay for subnanogram concentrations of adrenaline and noradrenaline in plasma (Tech. Rep. 787-1). Goleta, CA: Human Factors Research, Inc., 1970. (Also published in Analytical Biochemistry, 1970, 34, 568-581.)

Plasma assays for the catecholamines adrenaline (A) and noradrenaline (NA) typically had begun with extraction and product concentration. The more sensitive and specific chemical assays called for subsequent fluorometric determination of (A) and (NA) according to some modification of the classic trihydroxyindole (THI) method of Ehrlen (1948) and Lund (1949, 1950). Unfortunately, assays based on the THI method had not been sensitive enough to measure the lower concentrations of catecholamines found in normal plasma samples. For example, at the time this study began, no investigator had reported a convenient means of detecting (A) in concentrations below .05 ng/ml in 10-15 ml of plasma. Yet, this was the approximate mean value of (A) found by Klensch (1966) in 10 ml plasma samples from 95 humans at rest.

Some of the problems this had created for studying (A) in humans are obvious. Either one had to abandon hope of measuring the lower concentrations of (A) in plasma or he had to collect a very large quantity of plasma for a single determination. In the first case, the opportunity for defining the causes and effects of a decrease in plasma (A) is lost; in the second, there is a risk of seriously disturbing the homeostasis of the subject.

Using information published by Laverty and Taylor (1968), new separate reaction procedures were developed for maximizing the fluorescence from (A) and (NA) while holding the fluorescence from the other catecholamine to a minimum. These reaction procedures were added to a modified version of the extraction procedure of Anton and Sayre (1962). The result

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was a plasma assay for (A) and (NA) that was several times more sensitive than any previously reported. This methodology greatly facilitated the subsequent studies of behavior and the plasma catecholamines.

2. O'Hanlon, James F., Jr. Vigilance, the plasma catecholamines, and related biochemical and physiological variables (Tech. Rep. 787-2). Goleta, CA: Human Factors Research, Inc., 1970.

Vigilance, defined as the state of cerebral responsiveness to extraceptive or proprioceptive stimuli, had been the object of study by behavioral scientists for more than 25 years. Yet the biological basis for the vigilance decrement, or the failure to maintain an initial high level of vigilance under monotonous conditions, had not been well established. Theories offered to explain the vigilance decrement contained a common postulate: Vigilance is a function of cortical arousal which is mediated through activity within the reticular formation. The decline in the level of reticular activation was often held to be responsible for the vigilance decrement. The empirical data, though often ambiguous and contradictory, generally supported that position.

The first experimental study performed under this contract was designed to provide evidence for the existence of a relationship between (A) and vigilance. It was hypothesized that vigilance might be related to circulating concentrations of both adrenaline (A) and noradrenaline (NA). These hormones are excreted during stress, raising blood concentrations and producing a variety of physiological reactions. The mild stress involved in performing passive mental tasks elevates blood levels of both catecholamines but particularly (A). Circulating (A) also excites the mesencephalic reticular formation. Therefore, it had been suggested that a positive feedback relationship extends between the reticular formation and the adrenal medullae: A high level of reticular activation might produce a high rate of (A) secretion and a corresponding elevation in its blood level. The resulting high (A) concentration at receptor sites in the reticular formation would then perpetuate the initial level of reticular activation. This system could function to maintain high cortical arousal in vigilance.

Twelve young men performed as subjects on a simple signal detection task while seated in a specially constructed chamber which permitted the withdrawal of periodic blood samples from the subject without his awareness. The subject's task consisted of responding to each in a series of 1-second light pulses appearing on a visual display at a rate of once every 3 seconds. There were two types of pulses: the brighter was a signal; the dimmer a non-signal. After each pulse the subjects were to indicate one of four levels of confidence that a pulse was a signal.

Significant decreases in mean correct signal identifications, compared to alerted pre-watch performance, occurred during monotonous routine watchstanding. Mean (A) rose from its resting level under alerted conditions and then fell during monotonous conditions, as did mean galvanic skin response (GSR). Mean respiration rate (RR) rose under alerted conditions from its resting level and then fell progressively under monotonous conditions. Mean standard deviation of heart rate decreased under alerted conditions, then increased progressively under monotonous conditions. None of these changes was observed under a control condition in which the subjects merely viewed a series of disinteresting slide projections.

Average intra-subject correlations showed that (A), (GSR), and (RR) were positively related to correct signal identification and that the standard deviation of heart rate was inversely related to performance. No consistent relationships were observed for (NA).

The major conclusions of this study were that:

1. Catecholamine hormones are always active in the regulation of metabolic processes;

2. Physiological arousal increases from resting as subjects begin a vigilance task and declines to resting as their performance deteriorates during the task;

3. Heart rate variability is closely related to vigilance performance and this measure might be a valuable index of vigilance; and

4. Circulating (A) is related to vigilance as predicted.

3. O'Hanlon, James F., Jr., & Horvath, Steven M. Interrelationships among performance, circulating concentrations of adrenaline, noradrenaline, glucose, and the free fatty acids in man performing a monitoring task. Psychophysiology, 1973, 10(3), 251-259.

This report included further study of the relationships between (A) and (NA) and vigilance performance and the relationship of each of these variables with glucose (G) and the free fatty acids (FFA). The task and subjects were as before. The results showed inverse relationships between basal levels of both (A) and (NA) and (G). In the experimental condition, (A) initially increased, then declined in a manner parallel to performance. In the control condition, (A) declined to levels below the basal level. (NA) was not significantly different from the basal level at any time during either condition. (G) and (FFA) were elevated with respect to the corresponding basal levels under both conditions. The conclusions were:

1. (A) increased as a result of psychophysiological mobilization and declined in a manner related to performance;

2. (NA) was unrelated to performance;

3. (G) was high enough to ensure normal cerebral metabolism during the task; and

4. (FFA) increased simply as the result of attending to a changing visual environment in both conditions.

4. O'Hanlon, James F., Jr. Physiological and biochemical correlates of visual vigilance: Modification by carbon monoxide and hypoxia. Paper presented to the 79th Annual Convention, American Psychological Association, September 1971.*

This study was initiated by the widely recognized need for information concerning the behavioral effects of air pollutants. Specifically, its objective was to determine if vigilance is affected by typical urban concentrations of carbon monoxide (CO). On separate occasions, 10 male

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subjects were exposed for slightly longer than 2 hours to CO levels approximating the average (26 ppm) and peak (111 ppm) levels found over Los Angeles freeways. During the last 65 minutes of each exposure, the subject undertook a 3-minute pre-test followed, after a rest break, by a 60-minute vigil using the visual vigilance task employed for the earlier work on this contract. The subjects also undertook the task while breathing air without CO. The breathing mixture was administered through a face mask under normal atmospheric pressure.

Blood carboxyhemoglobin (COHb) levels were determined from blood samples drawn prior to exposure and before and after the test. The subject's heart rate (HR) was determined from ECG recordings and his minute ventilatory volume ($\dot{V}e$) and respiratory rate (RR) were recorded from the output of an electronic flowmeter.

The results showed that the blood COHb increased progressively during both exposures. After exposure for 2 hours to 26 ppm CO, mean COHb had risen from 0.8% to 2.3% of total hemoglobin. After a similar period of exposure to 111 ppm, COHb had risen from about the same base to 6.6%.

The lesser CO exposure had no significant effect on vigilance performance. However, the greater CO exposure exaggerated the typical performance decrement, so that the subjects were detecting on the average 10 to 20% fewer signals during the latter half of the vigil than they did under control conditions. This difference was highly significant.

No significant differences in HR, $\dot{V}e$, or RR were found between conditions.

The major conclusion from this part of the study was that exposure to peak urban CO concentrations for periods in excess of 1 hour impairs human capability for maintaining vigilance in visual monitoring tasks.

Work by Cahoon (1970) had shown that vigilance is deleteriously affected by apoxia experienced when breathing gas mixtures at normal atmospheric pressure which contain less than 12.8% O_2 (equivalent to P_{O_2} at a 13,000-foot altitude). A study was undertaken to confirm that finding and to relate it to concurrent biochemical and physiological changes. Eight male subjects were studied as they performed the visual

vigilance task while breathing, on separate occasions, 21% O_2 (sea level), 16% O_2 (8,000-foot equivalent), and 11.8% O_2 (15,000-foot equivalent) with the balance of the mixture being N_2. On each occasion, the subject first performed a 3-minute pre-test, then commenced breathing the selected gas mixture through a fixed mouthpiece while performing a 90-minute vigil.

The results showed that mean performance efficiency on the vigilance task was significantly poorer in the 11.8% O_2 condition than in the 21% O_2 condition. Performance in the 16% O_2 condition was poorer than in the 21% O_2 though not significantly so.

Mean (A) was generally higher in the 11.8% O_2 condition than in either of the other two conditions. Mean (A) rapidly increased during the first 10 minutes of exposure and later stabilized at a somewhat lower, but still elevated, level during continued exposure to 11.8% O_2. Individual differences in the increase of (A) from the 21% O_2 to the 11.8% O_2 condition were negatively related to concurrent changes in performance ($r = -.63$). Mean (NA) was generally unrelated to performance.

5. O'Hanlon, James F., Jr. Adrenaline's effects on human vigilance: Continuous vs. pulsatile infusions. Published in the Proceedings of the 79th Annual Convention, American Psychological Association, 1971.

Bonvallet, Dill, and Hiebel (1954) observed signs of arousal in the cortical EEGs of feline encéphale isolé preparations as they received minute intracarotid injections of adrenaline (A). Arousal was not seen after the projecting mesencephalic fiber tracts to the cortex were sectioned in these animals. Bonvallet et al. concluded that these results indicate the existence of a system, including midbrain arousal centers, elements of the sympathetic nervous system, and the adrenal medulla, which functions normally to maintain a level of vigilance conducive to effective behavior. By their reasoning, any event which arouses the animal also causes the release of (A) from the adrenal medullae. The surge of (A) in the circulation increases the hormone's excitatory action in the midbrain which, in turn, perpetuates cortical arousal and a high level of vigilance.

Much evidence, both supporting and repudiating this theory, had been offered. Earlier work under this contract had shown a positive relationship between endogenous circulating (A) and signal detection performance in men performing a visual monitoring task. The present study was designed to determine whether low rates of (A) infusion would increase vigilance in men performing the visual monitoring task. Positive results would provide evidence for the existence of a system such as that described by Bonvallet et al. in man.

The signal detection task was the same as employed in previous studies. Four levels of adrenaline infusion rate (.00, .01, .05, and .10 mg/kg/min) were employed. Under one condition the dosage was administered from a 50 cc syringe and a Harvard infusion pump on a continuous basis, delivering 3.8 ml/min. In a second condition, the pump ran at that rate for 30 seconds, then was off for 90 seconds, then on again for 30 seconds, and so forth. On/off switching was imperceptible to the subjects.

Bonvallet et al.'s theory was generally supported by the results of this study. Using pulsatile infusion, every subject's vigilance appeared to increase as a function of the (A) infusion rate. However, some subjects performed better with an intermediate infusion rate than with the highest rate used. Perhaps those subjects became overly aroused during the most rapid (A) infusion and were unable to attend as effectively to the task.

Corresponding constant and pulsatile infusions produced similar (A) excretion rates. Yet continuous infusions had little effect on performance, while pulsatile infusions improved performance significantly. This may be related to the frequently reported finding that the subjective effects of (A) diminish during constant (A) infusion (e.g., Frankenhaeuser & Järpe, 1963).

It seems that whenever the circulating (A) concentration is maintained at a high, relatively stable level, the central effects of the hormone begin to dissipate. This could occur if central (A) receptors cease to respond under those circumstances from "fatigue" or as a result of inhibition from another source. Regardless, the typically used

research procedure of administering (A) using constant infusions must now be reevaluated. It is possible that the results of previous (A) infusion studies have led to an underestimation of the normal psychophysiological effects of the hormone.

6. O'Hanlon, James F., Jr., & Beatty, Jackson.* Catecholamine correlates of radar monitoring performance. Biological Psychology, 1976, 4, 293-304.

Nearly all evidence relating catecholamine excretion rates and performance had arisen from laboratory or classroom situations where performance was tested using relatively unrealistic tasks. Some doubt remained concerning the generality of the relationship between these variables in real-life occupational tasks. This study involved two separate experiments in which catecholamine excretion rates were measured for both men and women who engaged in a simulated, but very realistic, radar monitoring task. This task was chosen because it is commonly thought that performance in practical monitoring situations is heavily dependent upon CNS arousal; that individuals vary widely in their abilities to maintain arousal under routine operating circumstances; that individual differences in arousal, as inferred from performance levels, might be related to catecholamine excretion rates; and that any demonstration of relationships involving catecholamines and radar monitoring would have practical as well as theoretical implications.

Eleven males and nine females served as subjects. Each was trained in target detection procedures using a cathode ray tube display in conventional Plan Position Indicator (PPI) format. The radar sweep line rotated at 10 rpm, painting continuous video noise and occasional single targets. The subject's task was to report the range and bearing of all suspected targets as quickly as possible. Catecholamine excretion rates were determined from urine samples taken from each subject both following a period of rest and at the completion of each test session. Catecholamine determination was made by the fluorometric assay previously developed for this project (O'Hanlon, Campuzano, & Horvath, 1970).

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The correlation between the excretion rate of (A) during the test was significant and in the expected direction ($r = -.54$; $p < .02$); the higher (A), the shorter the target detection latency. (NA) was found not to be significantly related to average radar watch performance. Further, neither catecholamine excretion rate, measured at rest, was significantly related to average radar watch performance, measured at a later time.

No significant differences were observed in the performance levels between male and female subjects nor in the (A) values for males and females. However, the male subjects showed a significantly higher level of (NA) excretion.

The results of this experiment were later confirmed in a second study involving a different group of 15 male and 13 female subjects. Again, (A) excretion rate correlated significantly ($r = -.506$; $p < .01$) with sweeps-to-detect scores. In this case, however, (NA) also significantly correlated with performance (-.508). This supported similar results reported by Frankenhaeuser, Nordheden, Myrsten, and Post (1971) who found significant correlations between both catecholamines and performance in a 90-minute test of sustained attention in the presence of distracting stimuli.

Average detection performance in both experiments tended to decline over time on watch, and individual changes in performance varied widely. Electroencephalographic (EEG) studies of subjects performing the same task indicated that these individual differences in performance were associated in part with differences in physiological arousal (Beatty, Greenberg, Deibler, & O'Hanlon, 1974). (A), measured during the test, was generally related to performance efficiency. The relationship was relatively strong and consistent in both experiments, being apparently unaffected by either the test duration or the sex of the subjects.

7. O'Hanlon, James F., Jr., & Beatty, Jackson. Occurrence of electroencephalographic and performance changes during a simulated radar watch and some implications for the arousal theory of vigilance. In R. R. Mackie (Ed.), Vigilance: Theory, operational performance, and physiological correlates. New York: Plenum Press, 1977.

In this final study of the physiological correlates of vigilance performance, attention shifted to the EEG as a physiological index

of operator alertness. Although several investigators had shown that electrocortical arousal progressively declines during vigilance tasks, few had shown any correlation between EEG and performance using a realistic monitoring task. The present study was designed as an attempt to simultaneously relate levels of Theta, Alpha, and Beta activity in the EEG to performance in a realistically simulated radar watch. As in the previous study, 20 subjects performed a task requiring visual search of a highly realistic simulated radar PPI display and reported the range and bearing of suspected target detections. The dependent measure was the number of successive target presentations before detection occurred (i.e., sweeps-to-detect).

Using a computer programmed to measure periods between positive-going zero crossings, sums and percentages of EEG waves in each of the traditional frequency bands (Delta, less than 3 Hz; Theta, 3 to 7 Hz; Alpha, 7 to 13 Hz; Beta, 13 to 30 Hz; or "noise," greater than 30 Hz) were calculated by 5-minute intervals. These data were further averaged by 30-minute periods to yield scores which coincided in time with average performance measurements over a 120-minute watch.

Differences among mean sweeps-to-detect and percentages of Theta, Alpha, and Beta waves in consecutive 30-minute periods of the watch were tested by separate analyses of variance. Significant relationships were observed between detection performance and the percentage of Theta, Alpha, and Beta in the EEG for successive 30-minute periods during the watch. The intrasubject coefficient of correlations between mean sweeps to detect and EEG measured in pre- and post-tests and in successive 30-minute periods of the watch was significant in each case: % Theta, $r = .44$; % Alpha, $r = .68$; % Beta, $r = -.67$.

The dominant rhythms of the waking cortex, Alpha and Beta, were generally observed to vary inversely over the conditions of this study. Within individuals, a greater occurrence of Alpha, and lesser occurrence of Beta, were equally well associated with a tendency toward poorer performance. The incidence of EEG waves in the Theta frequency range was always low, as might be expected for waking subjects. Nonetheless, slight variations in the relative frequency of Theta did occur, and these

were also significantly correlated with performance. Increasing Theta was associated with poorer performance.

The results of this experiment confirmed earlier findings and supported the hypothesis that both psychophysiological arousal and behavioral vigilance are manifestations of the same brain process. The major importance of this experiment is that it supported an extension of the arousal hypothesis of vigilance to a more realistic working environment. The vigilance decrement was first clearly defined from operational records of World War II radar operator performance (Baker, 1962). Nearly all of the subsequent research conducted in an effort to determine the psychophysiological bases of vigilance has involved the use of simplistic monitoring tasks. The question of whether arousal and performance are related in more complex and realistic tasks has remained moot. The vigilance decrement that was observed here in a simulated radar setting was not unlike demanding, real-world radar tasks. It was shown that electrocortical arousal was directly related to target detection efficiency. For that reason, previous psychophysiological studies, indicating essentially the same relationship, may now be generalized with greater confidence to explain operational performance changes.

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